Optimizing the usage of High Temperature Superconductor in direct drive wind turbines

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Optimizing the usage of High Temperature Superconductor in direct drive wind turbines

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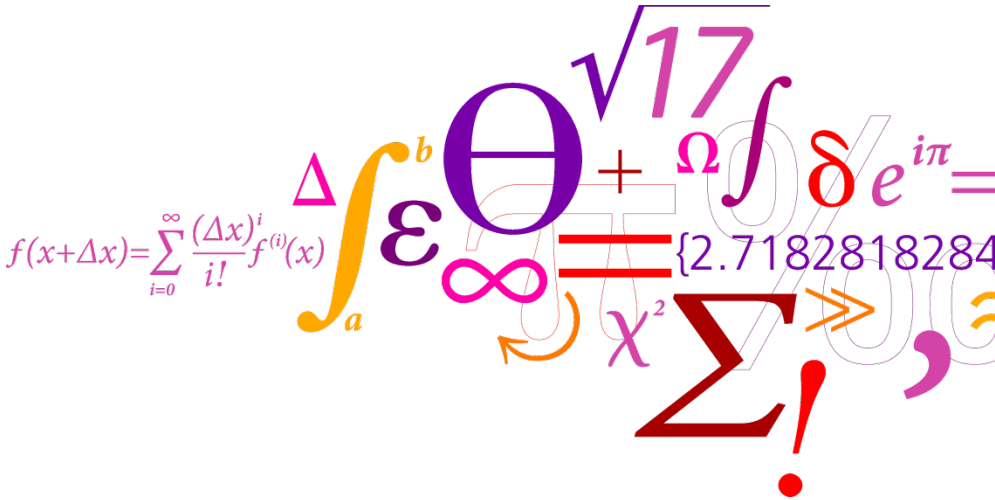
Pori, Finland



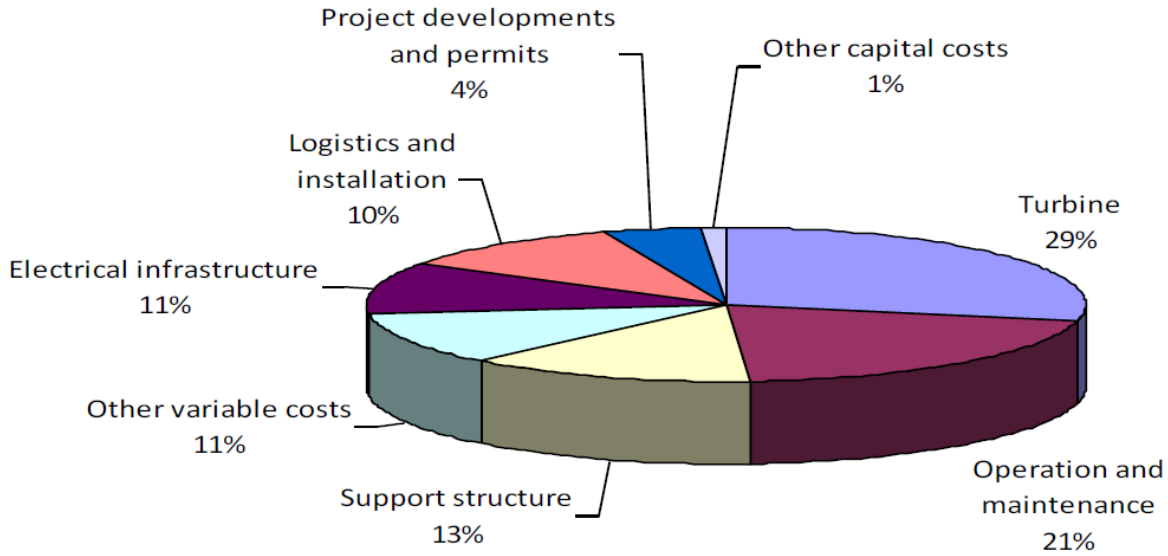
DTU Electrical Engineering

Department of Electrical Engineering

Offshore - Europe and World

	2020	2030	2050
Europe	40 GW	150 GW	460 GW
World	100 GW	375 GW	1150 GW

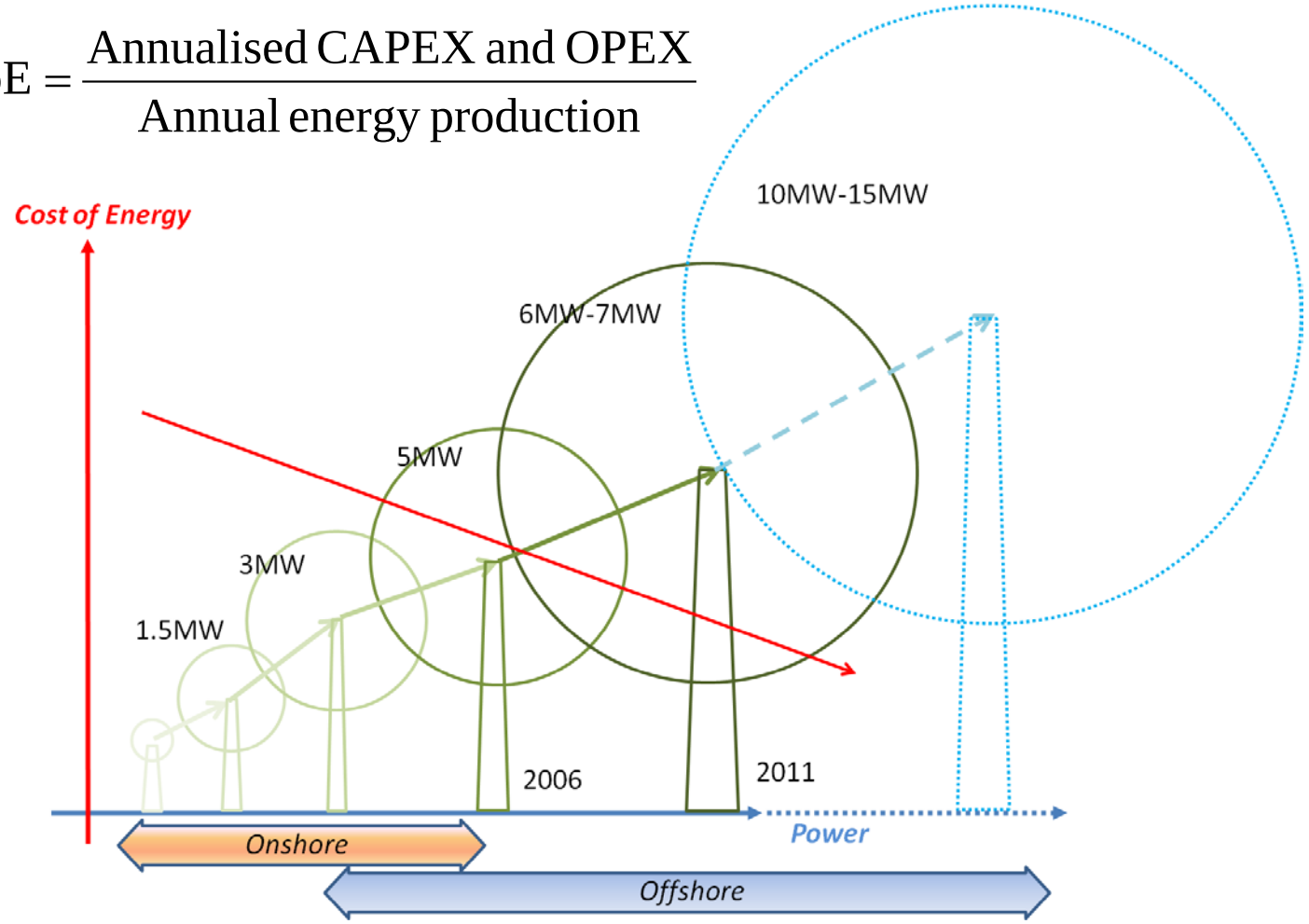
Source: EWEA



Source: Alexander Badelin, et al.Evaluation Programme Wind Energy in Germany, WMEP. 2006.

Wind Turbine Development

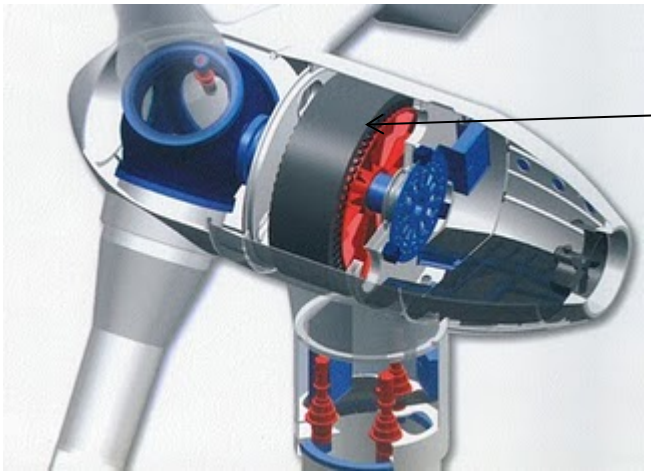
$$\mathrm{CoE} = \frac{\text{Annualised CAPEX and OPEX}}{\text{Annual energy production}}$$



PM in wind turbines

- A 6MW direct drive wind turbine is estimated to use 5 tons of permanent magnets

- This is the same as 2500 Toyota Prius



x2500

Motivation – Why propose superconducting wind turbine generators?

- They can become more compact than PMG

$$P = \omega T \qquad T \propto A \times \hat{B}_g \times V$$

$\cong$ $\cong$ $\uparrow$ $\downarrow$

A is the electric loading (amount of current in the stator per meter circumference)

$\hat{B}_g$ is the peak airgap flux density

V is the volume of a cylinder with the diameter of the airgap and the length of the machine (rotor volume in an inner rotor machine and stator volume in an outer rotor machine)

- They are less dependent on rare earth materials

	PMG	HTS
Medium speed	40kgR/MW (150kg PM/MW)	20gR/MW
Direct drive	200kgR/MW (750kg PM/MW)	100gR/MW

- Full-load efficiency is likely to be around 1.5% higher than a DD PMG

If it is so good, why has it not happened yet?

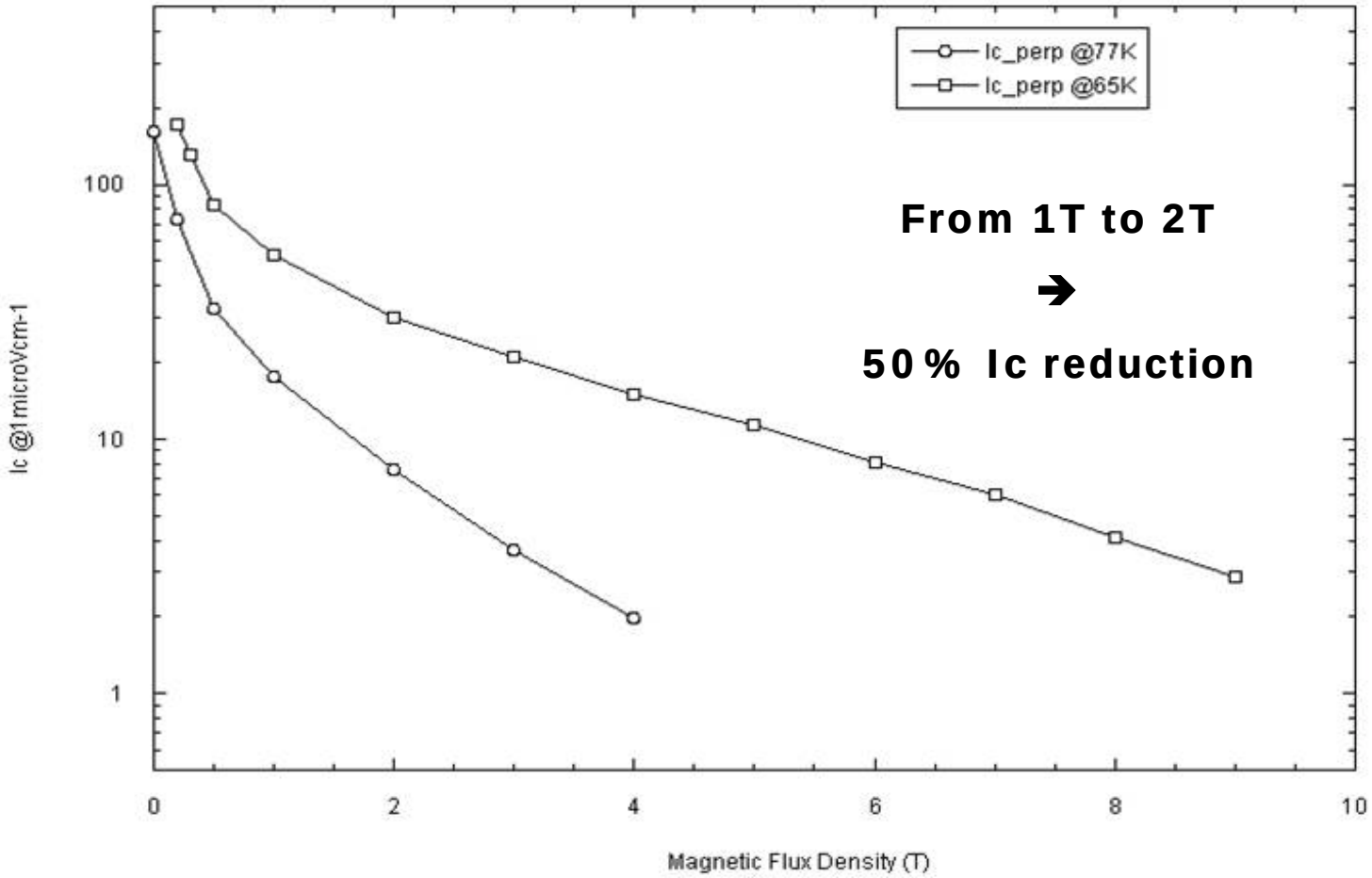
- Cost of Energy (€/kWh)

$$\mathrm{CoE} = \frac{\text{Annualised CAPEX and OPEX}}{\text{Annual energy production}}$$

- There are lots of challenges with superconductors!
  - Cooling and insulation vs. torque transfer
  - Reliability not proven
  - Very expensive technology that needs to come down by a factor of 20
  - Chicken and egg situation on the manufacturing of superconductors

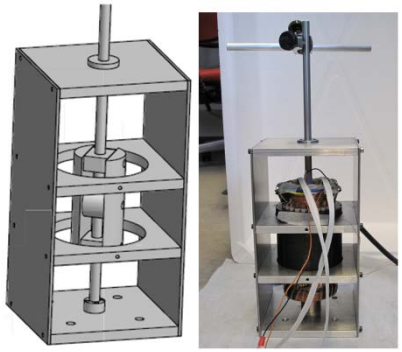
- Optimization of cost sensitive components is therefore crucial

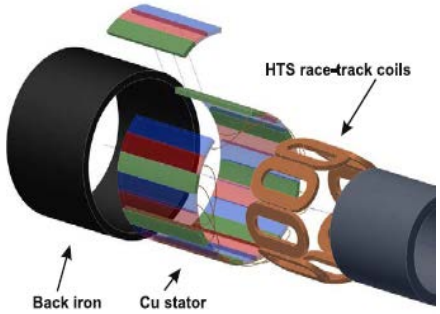
Superconductors:
Less current in high field



How do you learn about HTS machines? You build a few!

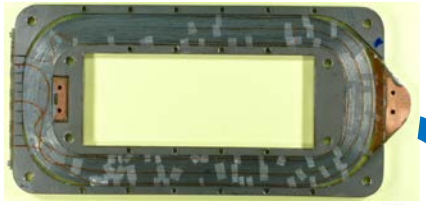
0.1kW

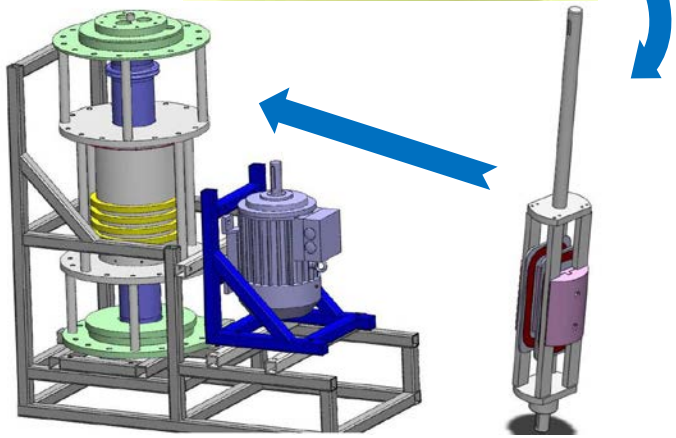




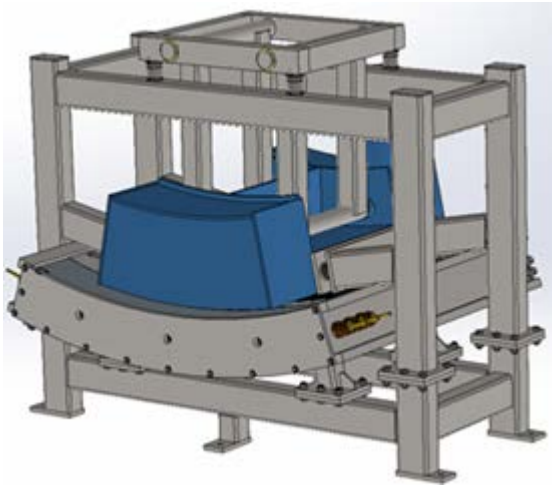
250kW

2kW

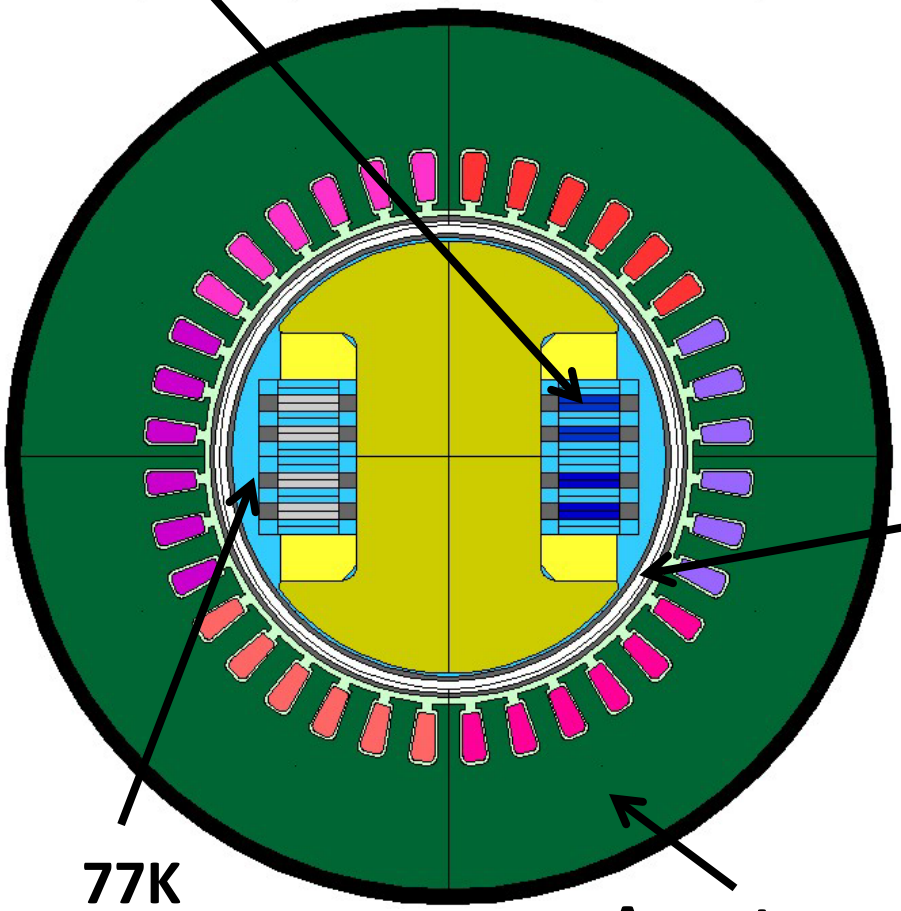


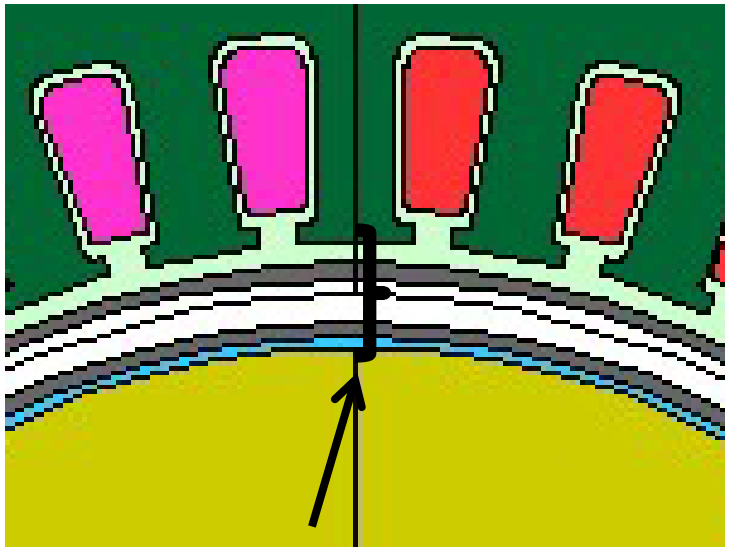


2MW



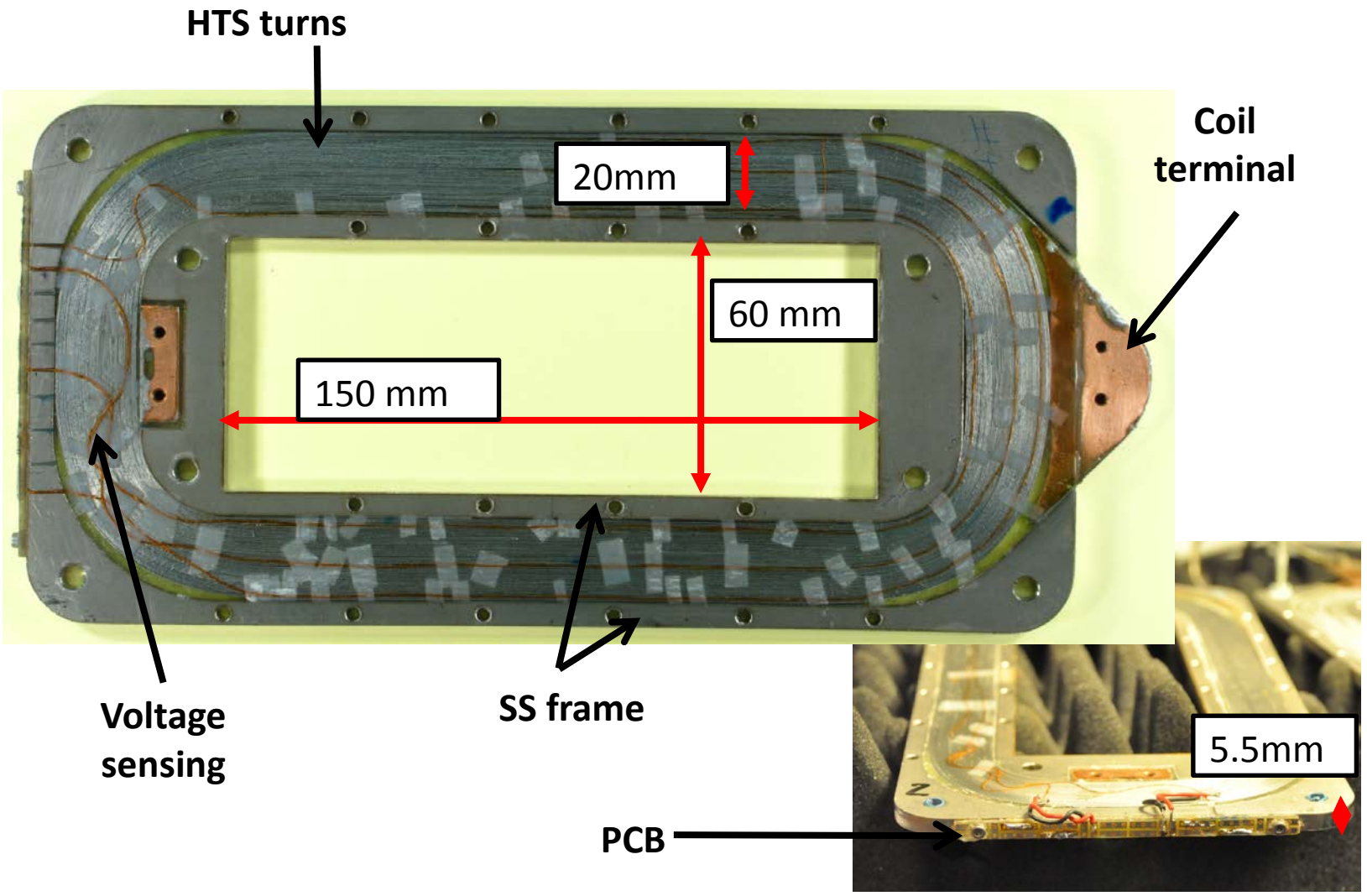
One of our modular machines



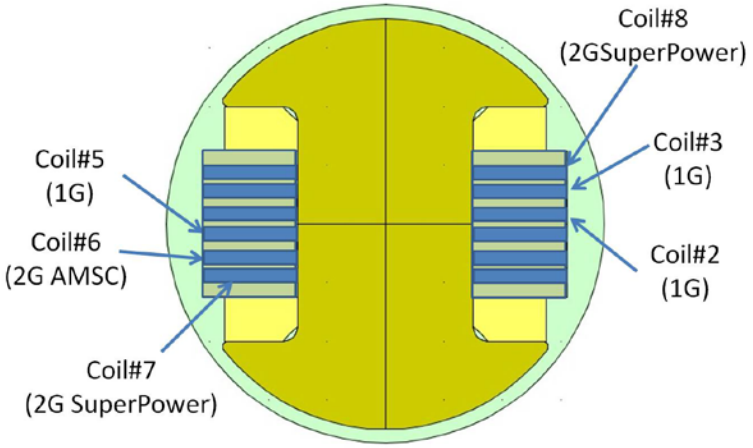


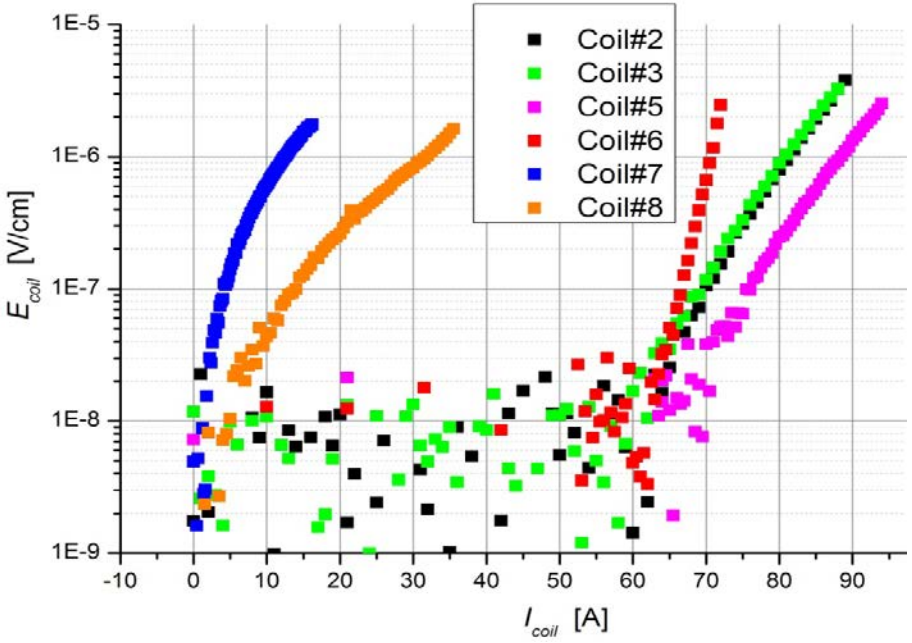
- Stationary field winding
- Cryostat with liquid N_2 (77K)
- Rotating Armature winding

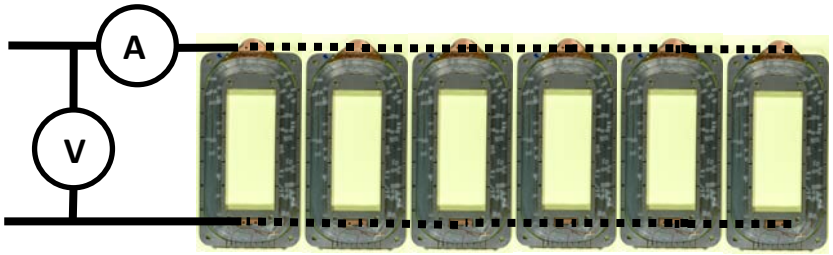
HTS coils:


HTS turns
20mm
Coil terminal
60 mm
150 mm
Voltage sensing
SS frame
5.5mm
PCB

Results (HTS coils – individually)



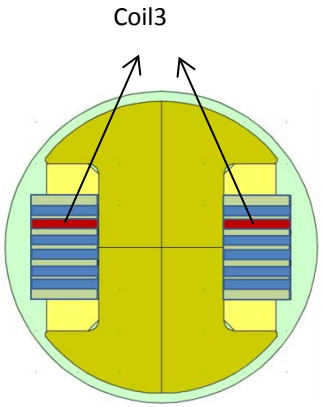


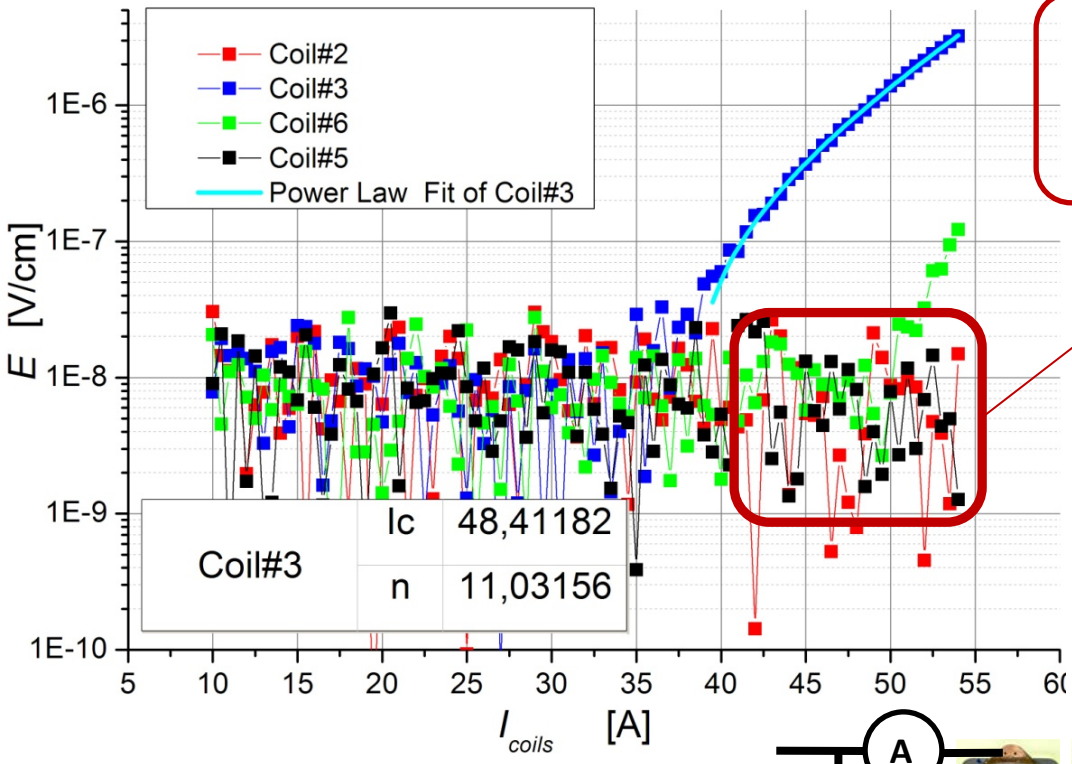


$$E = E_0 \left(\frac{I}{I_c} \right)^n \xrightarrow{Coil} E = \frac{V}{L} = E_0 \int_{L_{coil}} \left(\frac{I}{I_c} \right)^n dl$$

IV curves for serially connected coils

- The weakest link is the limiting factor

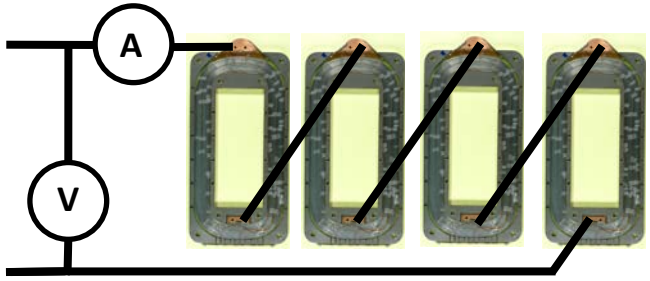




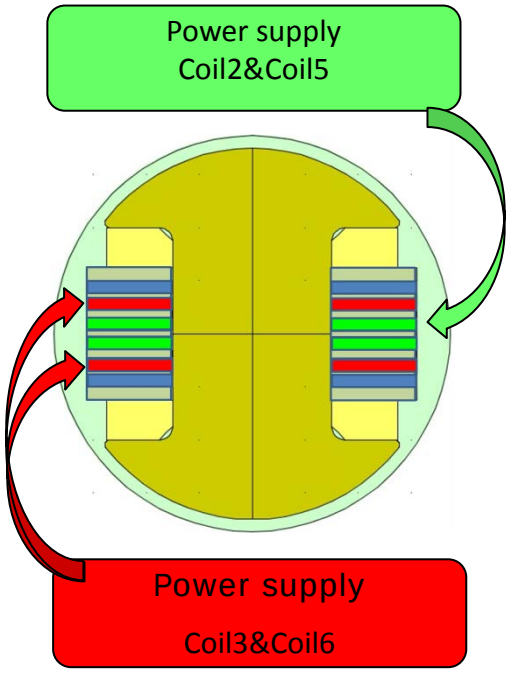
Coils with higher I_c

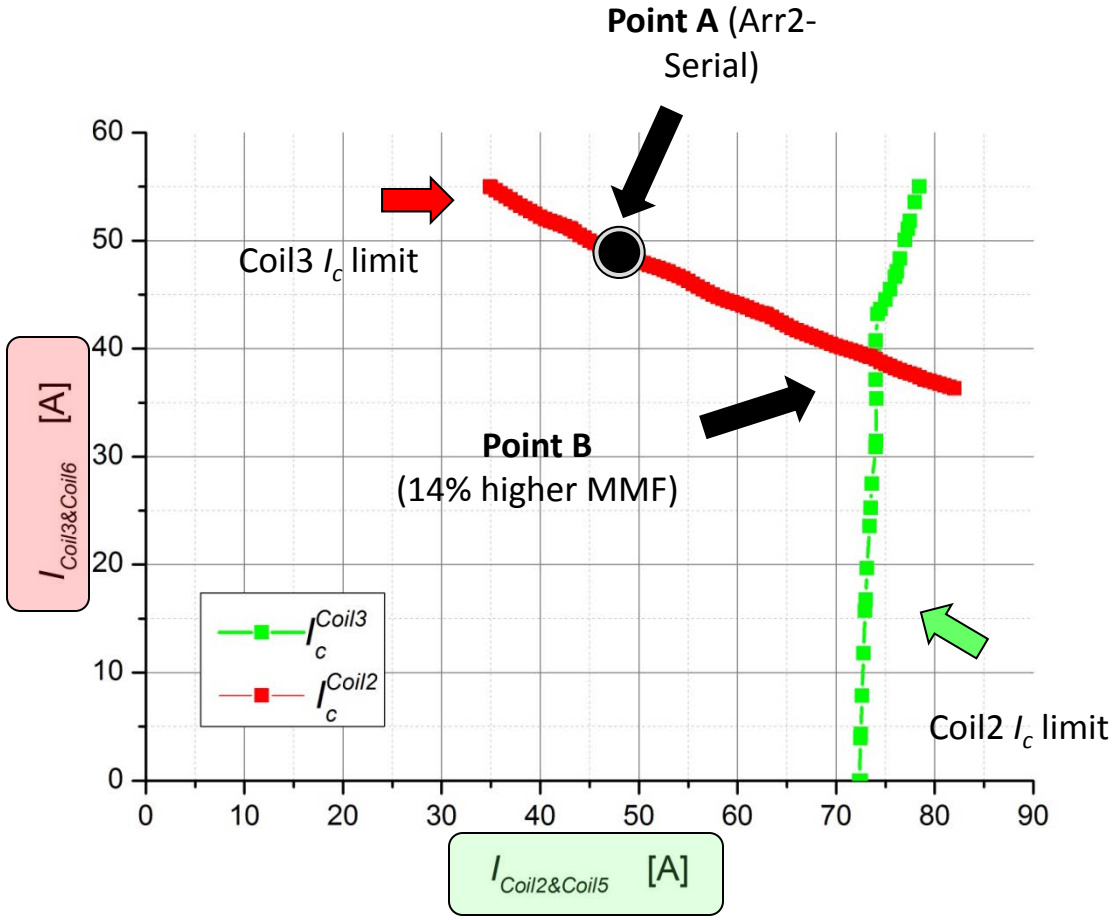
➔

Unutilized MMF



Two power supplies

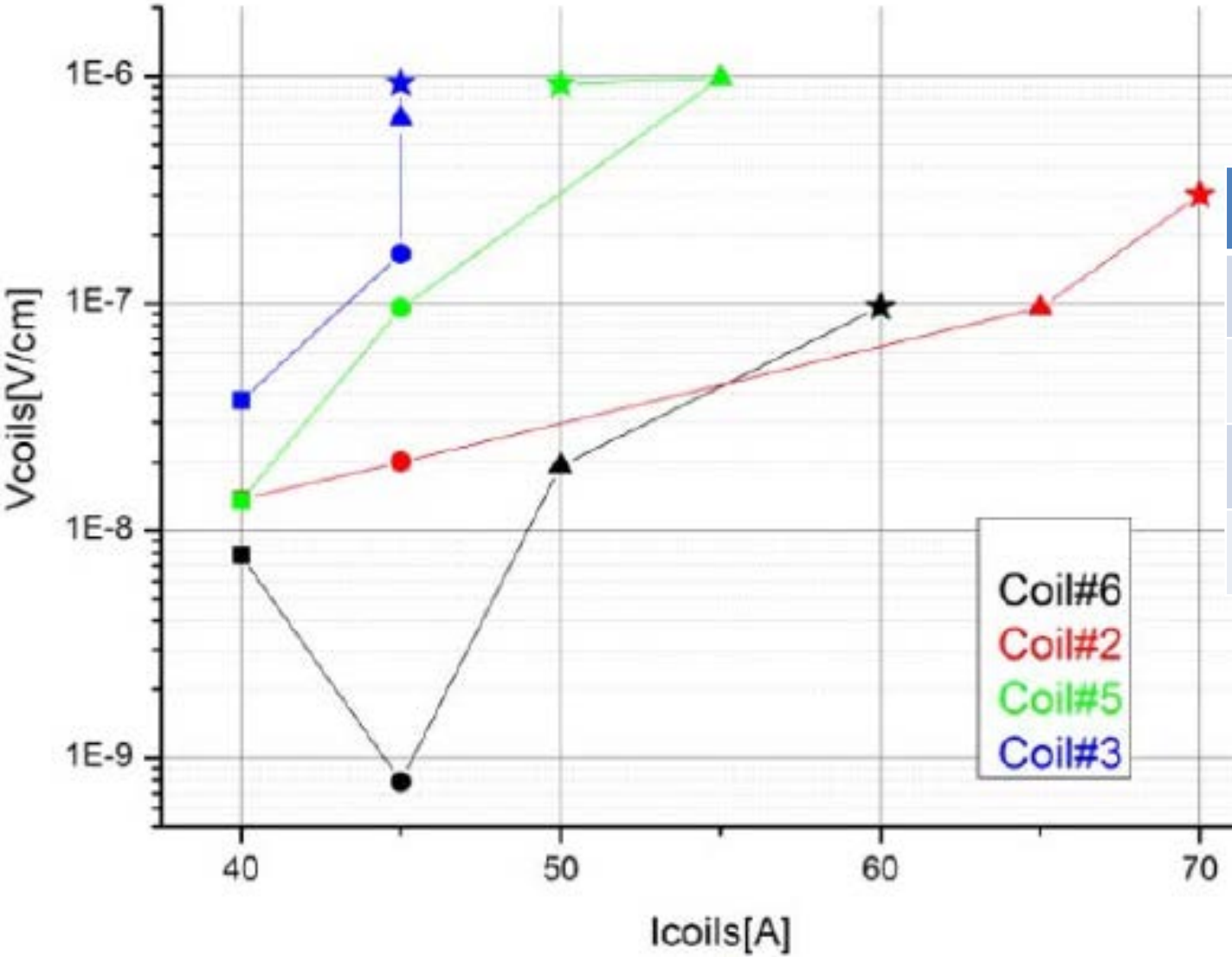




Point A: MMF = 9728A

Point B: MMF = 11130A (14.5% increase)

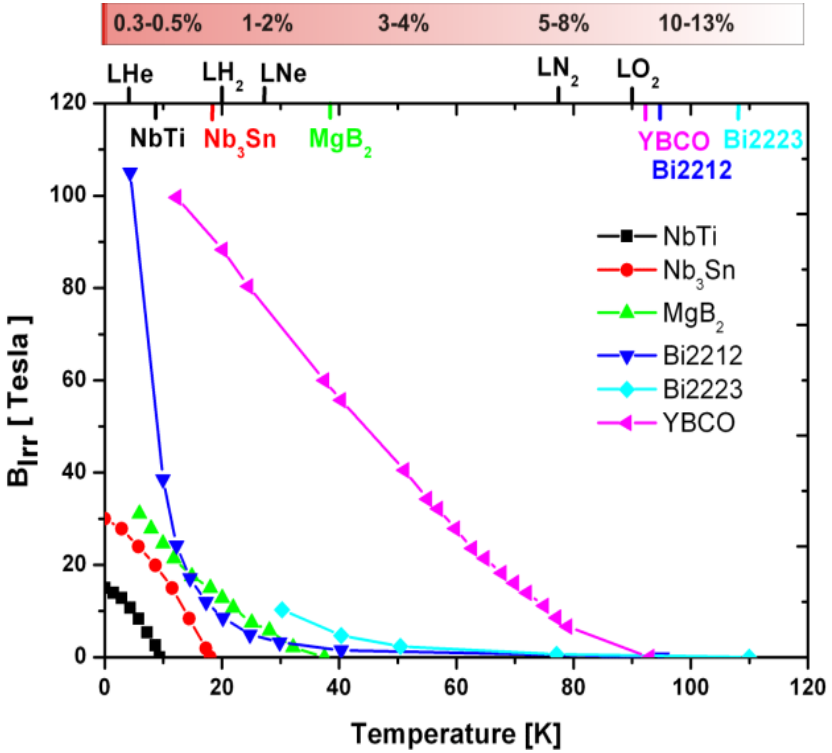
Up to 4 power supplies



MMF
9045 AT
10475 AT
11315 AT
13 368 AT

Overview of superconductors

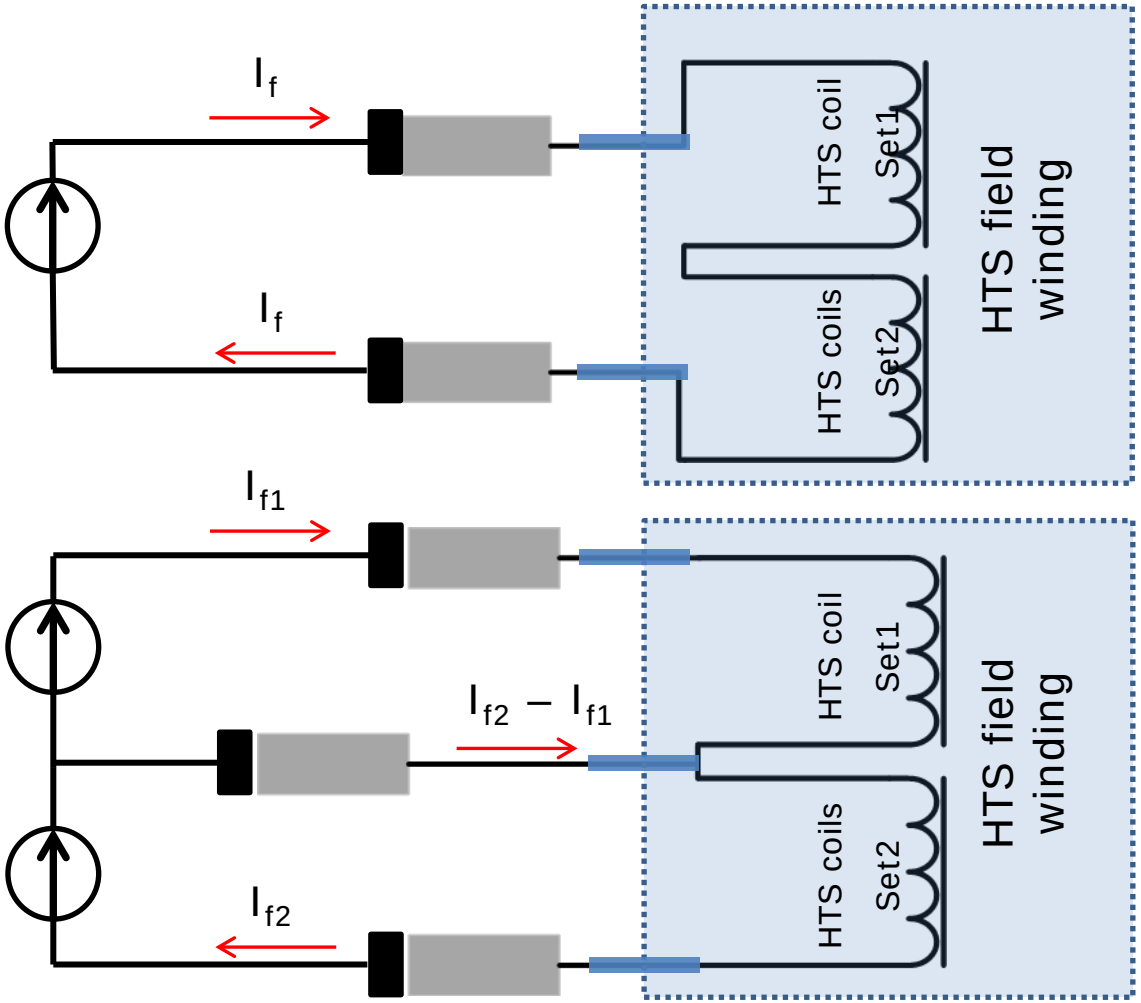
- Efficiency of the cooling system is seen above the graph



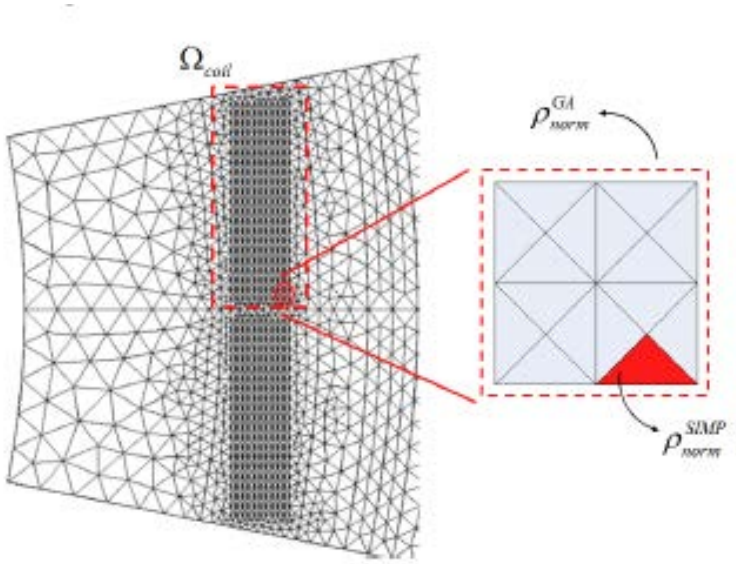
Type	Price €/m	J_e A/mm^2	Flux density [T]	Temp. [K]
NbTi	0.4	10^3	5	4.2
Nb_3Sn	3	1-4x10^3	5	4.2
MgB_2	4	10^2	3	20
Bi-2223	20	390 10	3 ⊥tape 3 ⊥tape	20 50
YBCO	30	98 (480) 49 (190)	3 ⊥tape 3 ⊥tape	20 50

B. B. Jensen, N. Mijatovic, A. B. Abrahamsen, "Development of Superconducting Wind Turbine Generators," *Journal of Renewable and Sustainable Energy – American Institute of Physics*, Vol. 5, pp. 023137, 2013. http://dx.doi.org/10.1063/1.4801449

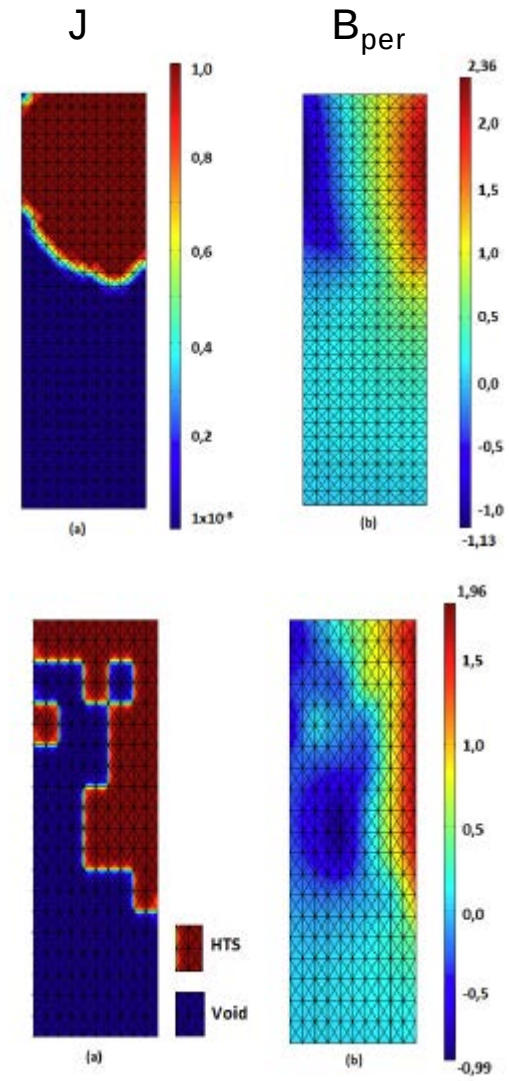
Current leads: Possible further optimization



Topology optimization

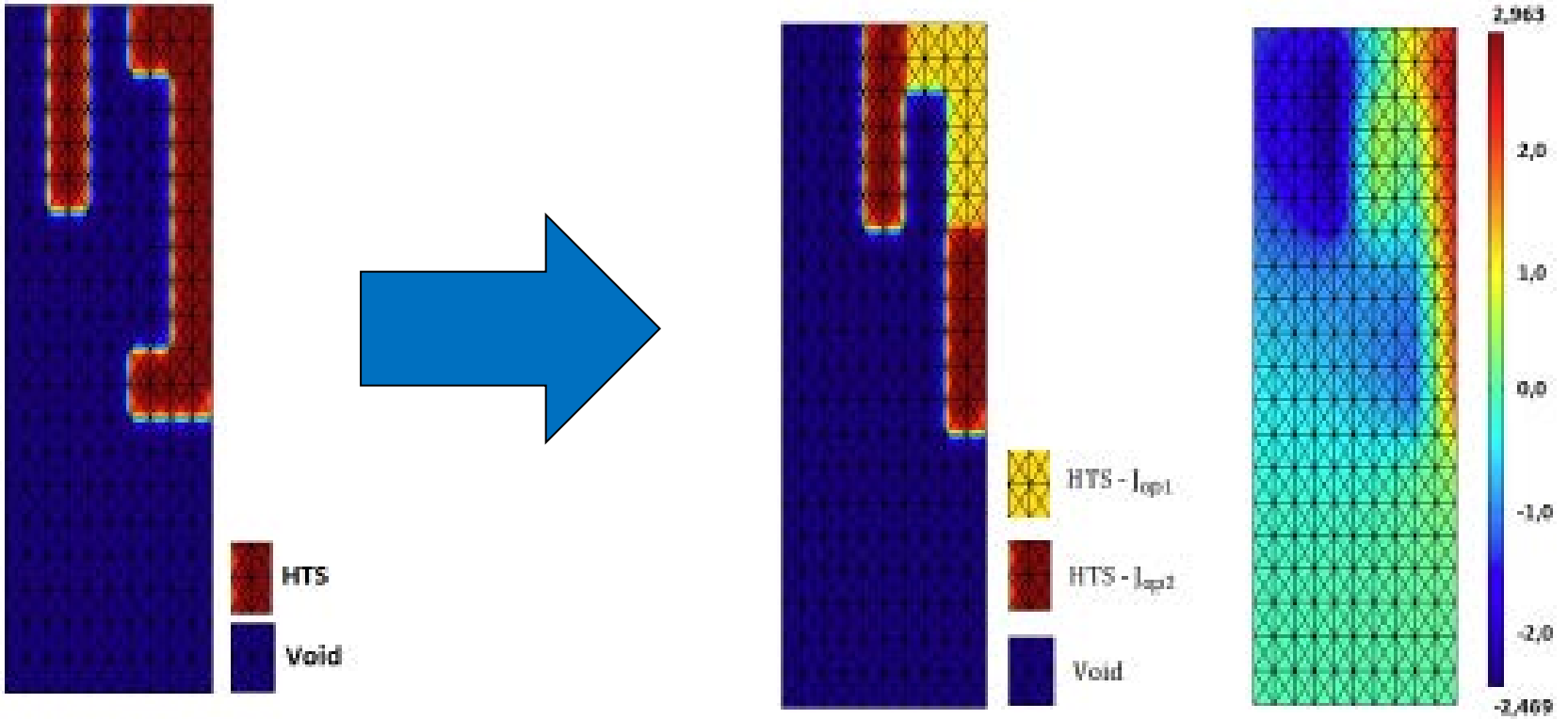


Optimization allocates HTS material based on objective function, e.g. minimal cost of HTS



Topology optimization – Two power supplies

- Adding power supplies adds complexity but also reduces the usage of HTS
- Best achieved results were in the order of 50% reduction



Conclusions

- Increasing the number of power supplies can reduce the HTS conductor usage by 30%

- Topology optimisation combined with multiple power supplies can reduce the conductor usage by up to 50%

- Future work:
  - introducing several types of conductors (grading)
  - optimization of the whole system including current leads, power supplies and HTS winding
  - Impact of proposed system on operation of HTS SM in wind turbines
- Thank you!

References and further reading

- B. B. Jensen, N. Mijatovic, A. B. Abrahamsen, “Development of Superconducting Wind Turbine Generators,” *Journal of Renewable and Sustainable Energy – American Institute of Physics*, Vol. 5, pp. 023137, 2013. http://dx.doi.org/10.1063/1.4801449
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